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Life-cycle energy analysis of building integrated photovoltaic systems (BiPVs) with heat recovery unit

R.H. Crawford[a,*], G.J. Treloar[a], R.J. Fuller[a], M. Bazilian[b]

[a]School of Architecture and Building, Deakin University, Geelong, Australia
[b]Sustainable Energy Authority of Ireland, Dublin, Ireland

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Abstract

Building integrated photovoltaic (BiPV) systems generate electricity, but also heat, which is typically wasted and also reduces the efficiency of generation. A heat recovery unit can be combined with a BiPV system to take advantage of this waste heat, thus providing cogeneration. Two different photovoltaic (PV) cell types were combined with a heat recovery unit and analysed in terms of their life-cycle energy consumption to determine the energy payback period. A net energy analysis of these PV systems has previously been performed, but recent improvements in the data used for this study allow for a more comprehensive assessment of the combined energy used throughout the entire life-cycle of these systems to be performed. Energy payback periods between 4 and 16.5 years were found, depending on the BiPV system. The energy embodied in PV systems is significant, emphasised here due to the innovative use of national average input–output (*I–O*) data to fill gaps in traditional life-cycle inventories, i.e. hybrid analysis. These findings provide an insight into the net energy savings that are possible with a well-designed and managed BiPV system.

Keywords: Life-cycle energy analysis; Building integrated photovoltaics; Embodied energy; Hybrid analysis

* Corresponding author. Tel.: +613 5227 8300; fax: +613 5227 8303.
E-mail address: robertc@deakin.edu.au (R.H. Crawford).

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Contents

1. Introduction

Energy consumption in Australia is steadily increasing, as a result of population growth and increasing standard of living [1]. This trend is producing an increasing demand on our dwindling resources and on the environment [2]. In 1994–1995 the operation of residential and commercial buildings in Australia accounted for around 20% of energy consumption [1].

The use of photovoltaics (PVs) is one approach that may assist in the minimisation of fossil fuel consumption. The electrical output from PVs is produced by the sun and is considered ‘free’ in environmental terms. However, they are mostly manufactured using fossil fuel intensive materials and processes. The energy consumed in the manufacture of PVs, commonly referred to as embodied energy, includes the energy for assembly and the energy embodied in the input of goods and services to the manufacturing process, including transportation in all mining and manufacturing phases [3]. The operation of PVs also produces thermal energy, primarily behind the PVs as a result of the generation of the electrical energy. A PV system has been designed to collect this (usually wasted) thermal energy, which is then used to heat the building when required.

The extent to which PV systems can save energy can be shown through a life-cycle energy analysis. This method determines the time it takes for annual operational savings to

overtake the energy embodied in a particular product, such as PVs, i.e. the 'energy payback period'. Previous studies have shown that the energy embodied in PV systems may be quite significant, depending on which embodied energy analysis method is used [4]. The extent of this significance has an impact on the amount of time required to pay this energy back. This paper presents the results of a life-cycle energy analysis of a building integrated photovoltaic (BiPV) system with a heat recovery unit using a newly developed hybrid embodied energy analysis method, considering recent improvements to this method, providing a more comprehensive analysis than has previously been possible.

2. Background

For traditional energy sources, the energy consumed at the point of use is lower than the energy required to supply this energy to the consumer, due to conversion and transmission losses and the energy embodied in the fuels and derivatives. The energy used by the consumer is known as delivered energy, while the base form of energy required is known as primary energy. For most renewable energy sources, such as BiPVs, the energy supplied requires no fossil fuels, and thus disconnects an entire sector of the economy and environment related to the production and distribution of power [5].

Traditionally, operational energy has been the focus of many studies dealing with life-cycle energy. This may be partly due to conceptual failure in quantifying the life-cycle energy requirements of products through underestimating the possible importance of embodied energy. Although the operational energy consumption of buildings accounts for the highest proportion of the total energy consumed in the life-cycle of a building, there is still a considerable amount of energy that is consumed in the other phases of a building's life. One of the most significant of these phases; incorporating the extraction and processing of raw materials, manufacturing of building materials and products and construction of the building; includes the embodied energy of the building and its fittings and finishes, but this varies significantly between building design, materials, systems and products. Embodied energy is particularly important due to the complexity of the supply chain. This complexity means that the supply chain has to be modelled for each product and process upstream to the raw materials.

2.1. Embodied energy

The embodied energy of an entire building, or a building material or product in a building, comprises of indirect and direct energy. Indirect energy is used to create the inputs of goods and services to the main process, whereas direct energy is the energy used for the main process (Fig. 1). The accuracy and extent of an embodied energy analysis is dependent on which of the three main methods is chosen: process analysis, input–output (*I–O*) analysis or hybrid analysis [5].

The process analysis method of embodied energy analysis is seen to have major limitations, most significantly, system boundary incompleteness. The most important stage of this method is the quantification of the inputs to the product or system. Traditionally, a boundary has been drawn around the quantification of inputs to

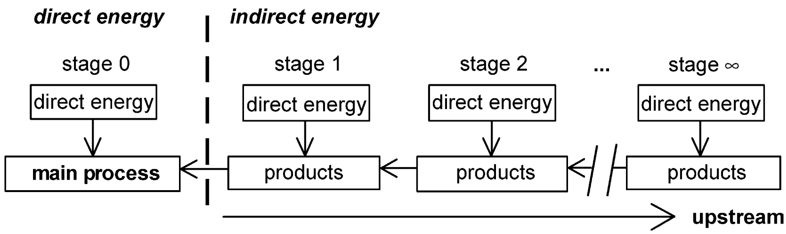

Fig. 1. Embodied energy analysis system boundary (after Boustead and Hancock [3]).

the product(s) being assessed, mainly due to difficulties in obtaining necessary data and the understanding of this data. Many inputs are therefore neglected in the quantification of inputs to a product, and thus the system boundary is incomplete. The magnitude of the incompleteness varies with the type of product or process and depth of study but can be 50% or more [5,6]. National average statistics that model the financial flows between sectors of the economy, referred to as *I–O* data, can be used to fill the gaps that are caused by system boundary incompleteness [5]. The use of *I–O* data in an *I–O* analysis is generally treated as a black box, with no understanding of the composition values being assumed in the model for each process. Also, because they are based on many inherent assumptions appropriate for national modelling, even a perfect *I–O* model may not lead to valid results for a particular product [7,8]. While *I–O* analysis is systemically complete, some *I–O* systems are inappropriately constructed, and may leave out significant aspects of the economy, as demonstrated by Lenzen [6] and Lenzen and Treloar [9] for capital investment. Some of the other main limitations of *I–O* analysis are detailed by Miller and Blair [10] and Lenzen [6] and include homogeneity and proportionality assumptions, sector classification and aggregation.

Due to the inherent problems with process analysis and *I–O* analysis, hybrid methods of embodied energy analysis have been developed in an attempt to minimise the limitations and errors of these traditional methods [11]. Hybrid methods combine process data and *I–O* data in a variety of formats [5,11,12]. The method chosen to assess the energy embodied in products, such as PVs, has an impact on the validity of the life-cycle energy results.

2.2. Past embodied energy studies of photovoltaics

Several studies have been performed on the embodied energy of PVs. One of the most comprehensive of these studies is that performed by Alsema [13] and Alsema and Nieuwlaar [14], in which an embodied energy figure for both crystalline silicon (c:Si) and amorphous silicon (a:Si)-based PV modules is presented. There seems to be, particularly with c:Si cells, some conjecture over the manufacturing processes to include in the quantification of the embodied energy of PVs, as is shown by Alsema [13] and Alsema et al. [15] and others (e.g. Refs. [16–19]). This variation is mainly due to the assumptions that are made regarding the silicon feedstock used to produce PV wafers. The majority of PV cells are currently made from 'off-grade' silicon from the semiconductor industry. Some studies treat the energy associated with the use of 'off-grade' silicon for PV cell

manufacture as free of embodied energy, whilst others partition some of the embodied energy associated with the semiconductor industry to the manufacture of PV cells using a variety of parameters. The other source of silicon feedstock is taken from the top and bottom of silicon ingots, which undergo an extra crystallisation step, thus requiring more energy. These different sources of silicon feedstock and methods of energy partitioning result in a considerable variation in the previously published estimates for the embodied energy of PV modules (0.6–4.6 GJ/m^2 of module area).

Due to the embodied energy analysis method used (process analysis), even the figures presented by Alsema and Nieuwlaar [14] for the embodied energy of the PV modules are incomplete, as a considerable number of inputs have been neglected in the quantification of inputs to the PVs. The incompleteness associated with their study can be demonstrated by the complexity associated with an *I–O* analysis of the PV modules [4]. It is for this reason that a more comprehensive method of hybrid embodied energy analysis should be used for the life-cycle energy analysis of PVs and most other products. The use of a hybrid method for assessing the energy embodied in PVs in order to minimise the limitations of previous studies is considered necessary despite the fact that the choice of whether to include the second crystallisation step in the production of silicon for the PV cells may have a much larger impact on the outcome of the embodied energy analysis.

A study by Crawford et al. [4] of the life-cycle energy consumption of the BiPV systems being considered in this current study used an embodied energy analysis method based on 1992–1993 *I–O* data. Since this previous study was published, the embodied energy analysis method has been updated with 1996–1997 *I–O* data, significantly improving the comprehensiveness and complexity of the previous method. The more recent data also includes the energy consumed in the manufacture of machinery and other capital equipment and buildings, commonly ignored or excluded in embodied energy analyses. This is due to the difficulty in determining the time that the equipment was used in production for amortising this capital energy [20]. This energy is as much a part of a product's life-cycle as any other direct or indirect input. Casler [21] has demonstrated that the quantification of capital energy requirements can be easily achieved through the use of *I–O* data. Lenzen and Treloar [9], Lenzen [22] and Gorree et al. [23] have estimated capital energy to account for between 10 and 17% of the total inputs of embodied energy to a product. Unlike many previous embodied energy analysis methods, the hybrid analysis method used in the present study considers the energy required for capital inputs. Whilst the inclusion of these capital inputs is systemically less significant compared to the use of the hybrid analysis method, its consideration provides a more comprehensive embodied energy assessment.

The issues discussed above give rise to two research questions to be addressed in the remainder of the paper

1. Does a BiPV system with heat recovery provide a life-cycle energy saving, considering a range of methods and scenarios?
2. Does a BiPV system with heat recovery pay back in primary energy terms before BiPV systems without heat recovery, considering a range of methods and scenarios?

3. Methodology

The evaluation of two BiPV systems with heat recovery units, one using c:Si PV cells and the other a:Si PV cells, involved the calculation of both the embodied energy and net electrical and thermal output to determine life-cycle energy consumption and thus energy payback periods. These figures were then compared to a BiPV system without the heat recovery unit, for which the embodied energy and net electrical output were also calculated.

3.1. System descriptions

The first system comprised two c:Si 75 W PV modules in aluminium frames with a total area of 1.26 m^2 and fixed to timber rafters. The second system was identical to the previous one with the addition of a heat recovery unit. This heat recovery unit, installed to collect the thermal energy produced by the PV modules, consisted of a 20 mm thick sheet of plywood, painted black, attached to the underside of the supporting rafters in order to create a duct behind the modules, covering an area of 1.92 m^2. A 6 W axial fan and DC brushless motor was attached to the low end of the duct to force the air through the heat recovery unit. All sides of the heat recovery unit were insulated with 50 mm of polyisostyrene. The third system was identical to the previous, using a:Si PV modules in place of the c:Si PV modules.

3.2. Life-cycle energy analysis

As PVs are used to reduce fossil fuel consumption, a life-cycle energy analysis of these systems involves a calculation of the output from such systems. BiPV systems are typically connected to an energy storage device, either a battery bank or the electricity grid so that a complete utilisation of the electrical output of the BiPV systems can be assumed.

The life-cycle energy analysis of the two BiPV systems with the heat recovery unit combines the embodied energy (considering the embodied energy credit from the displaced roofing materials), the electrical and thermal outputs, less the parasitic energy consumption, i.e. the energy required to power the fan. The life-cycle energy analysis of the BiPV system without the heat recovery unit, includes the embodied energy (also considering the embodied energy credit from the displaced roofing materials), and the electrical output. This analysis was performed for a period of 20 years as the greatest benefit will result if the payback periods are within the estimated life of the BiPV systems.

3.3. Embodied energy analysis method

A broad range of embodied energy figures have been presented in past studies, ranging from 0.6 GJ/m^2 [13] to 4.6 GJ/m^2 [14], due to the varying views on the silicon manufacturing processes to include in the analysis. In this study, two embodied energy figures were calculated, considering the range of approaches with respect to the production of silicon feedstock. In order to undertake the embodied energy analysis of the three BiPV systems, the quantities of materials used in the production of each of the systems were determined.

Information regarding components, materials, masses, areas and volumes was obtained from the manufacturers of the various products. All information was in the public domain.

Due to the complexities involved in calculating the process energy of the actual modules, and the availability of existing figures, the figures presented by Alsema [13], Alsema and Nieuwlaar [14] and Alsema et al. [15] for the embodied energy of both c:Si and a:Si modules were used for the basis of this study. The embodied energy values of the remaining materials, components and other inputs (e.g. module framing, fan, ductwork, plywood, and insulation) were derived using an *I–O*-based hybrid analysis method, as described by Treloar [5], using *I–O* data for Australia for the financial year 1996–1997. Various process analysis embodied energy data for major materials such as steel were also integrated with the *I–O* data [24]. While process data is not usually easy to obtain, its use is considered to maximise the reliability of the analysis at this stage. Further upstream indirect materials and processes are accounted for by either further applications of process analysis or *I–O* analysis when the process analysis data is unavailable or is considered too time consuming to collect relative to the significance of the process in question [5].

National *I–O* tables, produced by the Australian Bureau of Statistics [25] were combined with national energy data from the Australian Bureau of Agricultural and Resource Economics [26] to develop an energy-based *I–O* model of the economy. A number of these models have been developed for Australia, e.g. Refs. [5,27]. The *I–O* tables are divided into more than 100 sectors of the Australian economy, e.g. 'household appliances' , 'road transport', 'residential construction'. For each one of these economic sectors, a direct and total energy intensity can be calculated in units of GJ/\$1000 of product, representing the amount of energy used directly and in total to produce \$1000 worth of products from that specific sector. The *I–O* output theory underlying these calculations is extensively documented elsewhere [10,11,22,28,29] and shall therefore not be repeated here.

In a hybrid *I–O* analysis of any product, it is necessary to link the product's component breakdown to the economic sectors of the *I–O* classification in order to determine the energy intensities that should be applied. The capital energy inputs, usually excluded through an embodied energy analysis, are included in this procedure. The retail prices of the component breakdown of the BiPV system studied in our work were obtained from the supplier of the products, or if this was unavailable, an estimate was made based on literature and/or reasonable assumptions.

A number of hybrid material energy intensity figures, combining both process and *I–O* data, were derived. A hybrid energy intensity figure was calculated for all of the most common basic materials. These figures are expressed in GJ/unit (usually t, kg, m^2, m^3) of material and represent a simplified method of incorporating process data into the analysis, giving the amount of energy embodied in, for example, a kilogram of that material. For each basic material, the hybrid energy intensity (EI_M) was calculated using the typical Eq. (1).

$$EI_M = PEI_M + (TEI_n - TEI_M) \times \frac{\$_M}{1000} \tag{1}$$

where

PEI_M the material process energy intensity,
TEI_n the total energy intensity of *I–O* sector n, representing the basic material,

TEI_M the total energy intensity of the *I–O* path representing the basic material,
$\$_M$ the total price of the basic material.

Once the hybrid material energy intensities had been calculated, they were multiplied by the delivered quantities of basic materials of the BiPV systems. These individual material embodied energy figures were then summed to obtain the process-based hybrid analysis value for the BiPV systems.

The *I–O* model was disaggregated to allow the inputs for which process analysis data is available to be subtracted, leaving a remainder that was applied to the study in a holistic manner to fill all the remaining gaps, as demonstrated in Ref. [30]. From the inputs subtracted from the relevant sectors of the economy from which the product belongs ('sheet metal products', 'other electrical equipment' and 'residential building construction' sectors), the inputs that were counted in the process analysis inventory were identified (see Appendix A). The total energy intensity of each of the inputs represented in the process analysis inventory was subtracted from the total energy intensity of the sector. Whenever a process analysis value was available then the relevant input from the input extraction was subtracted from the total energy intensity of the sector to avoid double counting. The remainder of the unmodified inputs (the total energy intensity of the sector minus those inputs subtracted (GJ/$1000)) were then multiplied by the price of the product ($) and divided by 1000 to give the additional energy inputs (GJ) for the product. The process-based hybrid analysis value was then added to this figure, minus the direct energy component (as this is included in the remainder of unmodified inputs) to give the *I–O*-based hybrid analysis total (Table 1).

The energy embodied in maintenance, refurbishment and decommissioning was ignored in this study, due to the estimated relative insignificance of the associated energy over the life-cycle of the BiPV systems.

Table 1
Example *I–O*-based hybrid analysis of energy embodied in BiPV c:Si system

Process	Embodied energy (GJ/BiPV system)
Process data for materials	18.39
Input–output data used to fill upstream gaps	0.20
Process-based hybrid analysis data total	18.59[a]
Input–output data for 'other electrical equipment' sector	
Direct energy	0.3158
Total energy	30.248[b]
Inputs covering process data	7.86[c]
Remainder $^{(b-c)}$	22.38[d]
Total $^{(a+d)}$	40.97
Proportion of process data	44.9%

N.B. Displaced roofing materials have not been accounted for in this example for reasons of clarity.

3.4. Output analysis method

The BiPV systems were installed in Sydney, Australia (latitude 33.5°S), integrated with a full-scale insulated, framed and roofed residential roofing and wall system.

The electrical output of the BiPV systems was monitored and logged using LabView. A variable resistor was used to load each system. At intervals in line with the acquisition of the thermal data, the open circuit voltage, short circuit current, and voltage and current at maximum power were recorded. The power output was also logged into the system. An inverter was not used at the test site and thus the power production was DC electricity.

The thermal data was measured by a series of type T thermocouples placed on surfaces and in the fluid flow of the various units in a grid pattern. The thermocouples were calibrated prior to insertion and have custom spot welds distinctly created for measuring surface temperatures or air temperatures. The thermocouples were queried every 15 s over a typical 1 min interval, averaged, and then logged into a DataTaker 800. The duct velocity was measured with a highly sensitive hot wire anemometer. The environmental monitoring was done on site with a pyranometer, a wind velocity transducer, and a temperature/RH meter.

Thermal energy consumption in buildings is commonly supplied by both gas and electricity, with gas usually being used where it is available. Therefore, in order to provide a more detailed comparison, the delivered energy output figures from the BiPV heat recovery units were converted to both gas- and electrical-based primary energy outputs. The electrical output figures were then added to these gas- or electrical-based thermal output figures, and the energy required to power the fan subtracted, to obtain a total output for each of the BiPV heat recovery systems.

4. Results and discussion

The energy payback period for each of the three systems involves determining the point at which the energy invested in the manufacture of each system (the embodied energy) is 'paid back' by the savings in energy output.

There were four scenarios used to evaluate the BiPV heat recovery systems

1. high embodied energy and electrical-based thermal output;
2. high embodied energy and natural gas-based thermal output;
3. low embodied energy and electrical-based thermal output; and
4. low embodied energy and natural gas-based thermal output.

It was assumed that gas is used for thermal energy supply where it is available, and electricity would be used where gas is unavailable.

4.1. Embodied energy

The embodied energy of each of the three BiPV systems is shown below in Table 2. The units of embodied energy are gigajoules of primary energy (1 GJ$=10^3$ MJ). Figures based on the different approaches with respect to the production of silicon feedstock are presented (i.e. low and high figures).

Table 2
BiPV system embodied energy (GJ)

Manufacturing process embodied energy level	BiPV c:Si	BiPV c:Si HRU	BiPV a:Si HRU
Low	27.49	45.41	31.62
High	37.82	55.74	32.75

4.2. Net output

The output of the BiPV system was converted to primary energy terms, to account for conversion and transmission losses and the energy embodied in the fuels and derivatives. A primary energy factor of 3.1 was used as this would be typical for New South Wales [5]. The primary energy-based electrical output of each BiPV system is shown in Table 3.

Table 3
BiPV system primary energy-based electrical output (GJ/annum)

BiPV c:Si	BiPV c:Si HRU	BiPV a:Si HRU
2.33	2.43	1.85

The thermal output from the heat recovery units was also converted to primary energy terms. Thermal energy consumption for buildings is commonly supplied by natural gas or electricity. The thermal output delivered energy figures were therefore converted to primary energy figures for gas and electricity to allow comparison, using conversion factors of 1.4 and 3.1 for gas and electricity, respectively [5]. Efficiency utilisation factors were also used for both fuel types (0.7 for gas and 1.0 for electricity). The equivalent primary energy-based thermal output from the two BiPV heat recovery systems is shown in Table 4.

Table 4
BiPV heat recovery system primary energy-based thermal output (GJ/annum)

Thermal equivalent	BiPV c:Si HRU	BiPV a:Si HRU
Electrical-based	5.10	5.80
Gas-based	1.61	1.83

The total combined output of each of the two BiPV heat recovery systems was calculated by adding the thermal and electrical output for each system and subtracting the fan energy use. The energy required to power the fan was measured at 0.0263 GJ/annum. The total output of each BiPV system is shown in Table 5, showing the total output for gas- and electrical-based thermal output for the two BiPV heat recovery systems.

Table 5
BiPV system net output (GJ/annum)

Thermal equivalent	BiPV c:Si	BiPV c:Si HRU	BiPV a:Si HRU
Electrical-based	2.33	7.50	7.63
Gas-based	2.33	4.02	3.66

4.3. Life-cycle energy analysis and payback periods

Fig. 2 shows that although the BiPV c:Si heat recovery system has the highest embodied energy of all three systems, for the high embodied energy and electrical-based thermal output scenario, the energy payback period of this system is only 7.5 years, indicated by the point at where it crosses the x-axis, compared to 16.5 years for the BiPV c:Si system. The BiPV a:Si heat recovery system has the lowest embodied energy of the three systems and also the shortest payback period, of around 4.3 years. It is therefore evident that the addition of the heat recovery unit improves the energy pay back period of a BiPV c:Si system by 9 years, for this scenario. Even considering the additional embodied energy of the heat recovery system its use halves the energy payback period of the BiPV c:Si system.

Whilst the BiPV a:Si heat recovery system has only a slightly higher net annual output than the BiPV c:Si heat recovery system (Table 5), for the high embodied energy and electrical-based thermal output scenario (Fig. 2), it also has 40% less embodied energy (Table 2). This has had a greater impact on the payback period of the BiPV a:Si heat recovery system than the slightly higher annual output has, lowering it by 3 years.

Fig. 3, showing the gas-based thermal output scenario, shows the significant impact that this has on the payback periods of the three systems. Although the BiPV c:Si system still has a payback period of 16.5 years, as it does not contain a heat recovery unit, the BiPV c:Si heat recovery system has a payback period of 14 years increasing its payback period by 6.5 years when compared to the electrical-based thermal output scenario (Fig. 2). Basing the thermal output on gas has also doubled the energy payback period of the BiPV a:Si heat recovery system to 9 years. This is mainly due to the reduced primary energy thermal output of

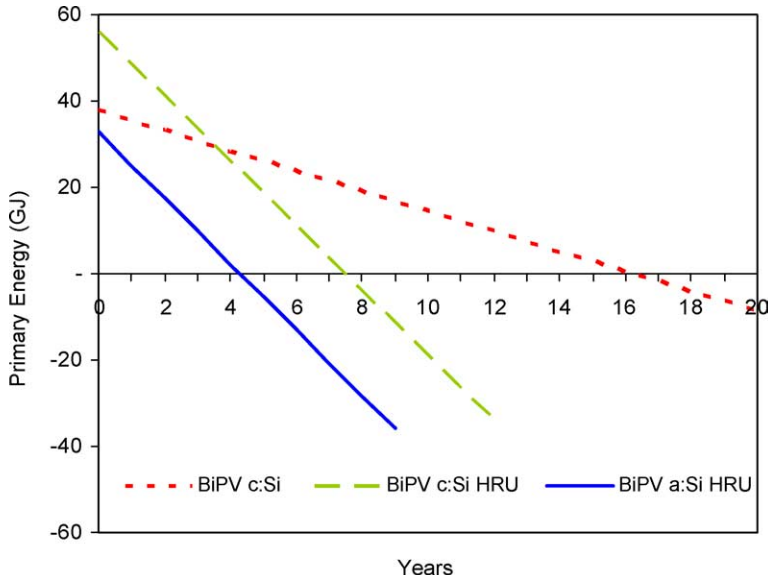

Fig. 2. BiPV energy payback periods (high embodied energy and electrical-based thermal output scenario). N.B. ‘0’ years = embodied energy.

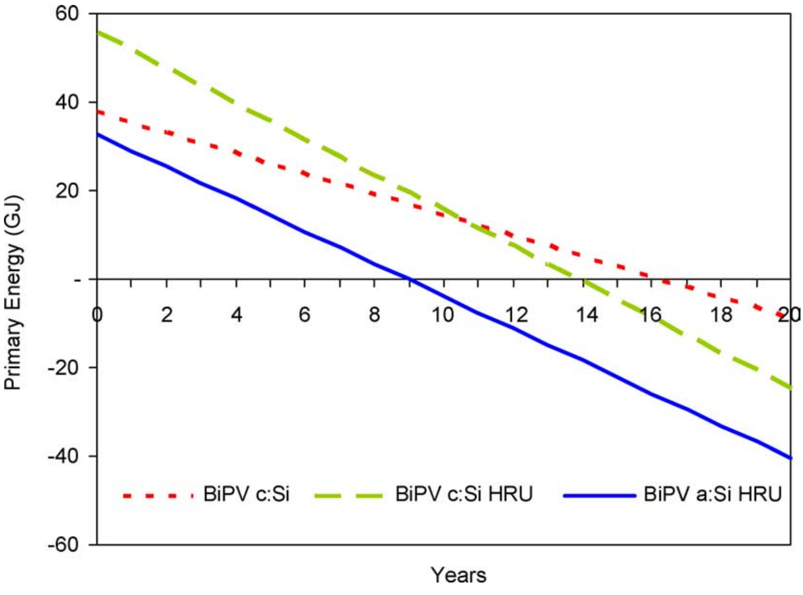

Fig. 3. BiPV energy payback periods (high embodied energy and natural gas-based thermal output scenario). N.B. ‘0’ years = embodied energy.

the system. In this situation, the embodied energy has a much greater impact on the energy payback periods of the two heat recovery systems, as it is more dominant over their life-cycle.

Fig. 4, showing the low embodied energy and electrical-based thermal output scenario, shows the impact of the lower embodied energy figure. The payback period of the BiPV c:Si system has reduced by almost 4.5–12 years, compared to the high embodied energy scenario (Figs. 2 and 3), as the net energy consumption of this system is dominated by its embodied energy, with no thermal output. As the payback periods of the two heat recovery systems are dominated by their output, the impact of the lower embodied energy figure is not as great. The energy payback period of the BiPV c:Si heat recovery system has been reduced to 6 years, a reduction of 1.5 years, and as the difference between high and low embodied energy figures for the a:Si heat recovery system is not great, the payback period of this system has had only a minimal reduction.

Fig. 5, showing the low embodied energy and gas-based thermal output scenario, shows the affect that both of these variables have on the payback period of the three systems. When compared to the electrical-based thermal output scenario (Fig. 4), the payback period of the BiPV a:Si heat recovery system has increased by 4.5 years to just over 8.5 years. For the BiPV c:Si heat recovery system the payback period has increased by 5.5–11.5 years. The lower embodied energy figure has meant a smaller impact on payback periods due to the gas-based thermal output. When compared to the high embodied energy figure and gas-based thermal output scenario (Fig. 3), the payback period of the BiPV c:Si system has reduced by 4.5–12 years and for the BiPV c:Si heat recovery system by 2.5–11.5 years.

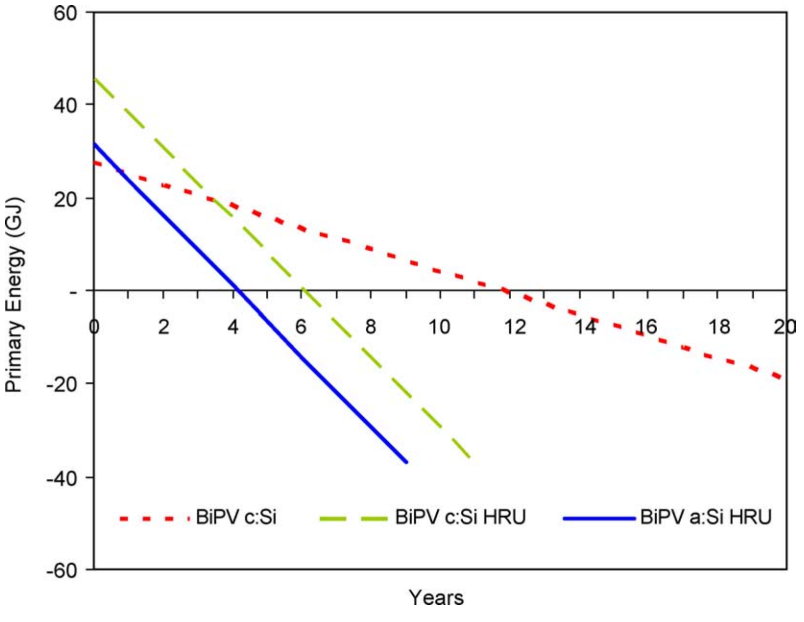

Fig. 4. BiPV energy payback periods (low embodied energy and electrical-based thermal output scenario). N.B. '0' years = embodied energy.

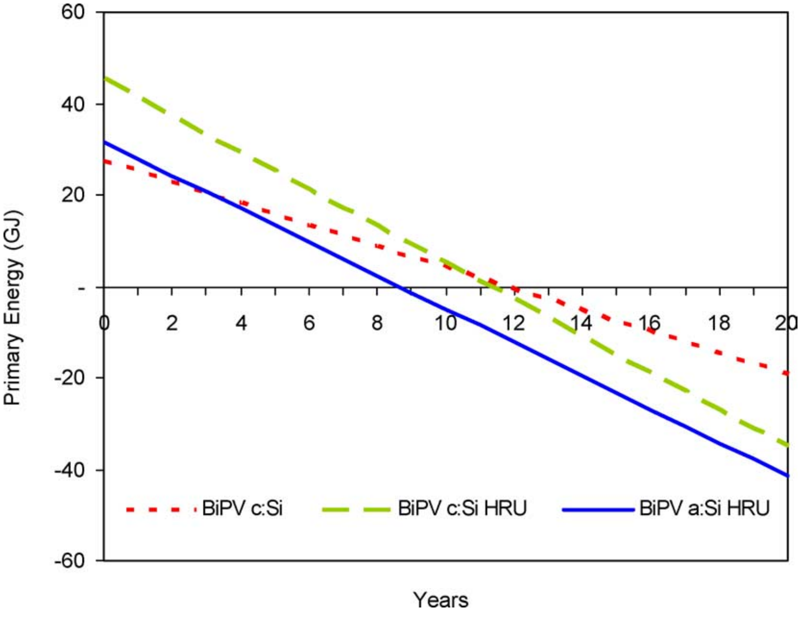

Fig. 5. BiPV energy payback periods (low embodied energy and natural gas-based thermal output scenario). N.B. '0' years = embodied energy.

The recent improvements to the embodied energy analysis method used in this study, together with the use of more recent *I–O* data and the inclusion of capital energy inputs has had a significant impact on the energy payback periods of the BiPV systems compared to previous studies. The study by Crawford et al. [4] resulted in payback periods ranging from 2.5 to 9 years for the two BiPV heat recovery systems and up to 10 years for the BiPV c:Si system. In the current study these payback periods have increased by 40%. This increase is due to the equivalent increase in the embodied energy values of the respective BiPV systems, as a result of improvements made to the *I–O* model used for the embodied energy assessment.

5. Conclusions

It is evident from this study that the embodied energy component of the three BiPV systems analysed becomes more significant for situations with lower energy output. The magnitude of the embodied energy figure used in the analysis has a significant impact on the energy payback period of the BiPV c:Si system but the value used is not significant for the two BiPV heat recovery systems. The use of the heat recovery unit integrated with a traditional BiPV system has been shown to almost halve the energy payback period of traditional BiPV c:Si systems. However, when the thermal output of the heat recovery systems is assumed to displace gas, these energy payback periods can double because now the embodied energy component accounts for a greater proportion. Regardless of this, in both of these situations the use of the heat recovery unit provides substantial life-cycle energy savings.

The energy payback period of the BiPV c:Si system ranges from 12 to 16.5 years. The energy payback period of the BiPV a:Si heat recovery system ranges from 4 to 9 years for both high and low assessments of embodied energy and both electrical- and gas-based thermal output situations. For the BiPV c:Si heat recovery system the payback period ranges from 6 to 14 years depending on which scenario is considered. Whilst the energy payback period differs from one scenario to the next, this study has shown that all three of the BiPV systems considered will pay back in energy terms within their predicted life of at least 20 years. The energy payback period depends on

- the process analysis figure that is used for the embodied energy (either high or low);
- whether a hybrid embodied energy analysis method is used;
- the location, electrical and thermal output and degree of utilisation; and
- whether the thermal output for the heat recovery systems is gas- or electrical-based.

The use of a heat recovery unit in combination with a BiPV system has shown to reduce the energy payback period of a typical BiPV system.

Where electricity is the only option, building occupants may also consider buying ‘green’ tariff electricity (which reduces dependence on fossil fuels and greenhouse gas emitting sources), to further reduce the emissions associated with the operation of buildings and their associated functions.

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Appendix A

Most significant inputs in the ‘other electrical equipment’ sector of the input–output model for the BiPV systems (GJ/$1000).

DEI	TEI	Stage 1	Stage 2
1.6410	*4.1409*	*Basic non-ferrous metal and products*	
0.9568	1.7821	Basic chemicals	
0.6433	1.2590	Iron and steel	
0.4091	1.0322	Basic non-ferrous metal and products	Basic non-ferrous metal and products
0.2632	0.4903	Basic chemicals	Basic chemicals
0.2010	0.5073	Other electrical equipment	Basic non-ferrous metal and products
0.1847	14.5807	*Direct energy required by ‘other electrical equipment’*	
0.1463	0.2863	Iron and steel	Iron and steel
0.1422	0.2252	Air and space transport	
0.1352	0.2645	Structural metal products	Iron and steel
0.1279	0.2111	Ceramic products	
0.1229	0.1772	Road transport	
0.1224	0.4706	Basic non-ferrous metal and products	Non-ferrous metal ores
0.1191	0.2330	Other machinery and equipment	Iron and steel
0.1172	0.2183	Other electrical equipment	Basic chemicals
0.1020	0.2573	Basic non-ferrous metal and products	Basic non-ferrous metal and products
0.0864	0.1609	Plastic products	Basic chemicals
0.0788	0.1542	Other electrical equipment	Iron and steel
0.0512	0.1002	Fabricated metal products	Iron and steel
0.0501	0.1264	Other electrical equipment	Basic non-ferrous metal and products
0.0364	0.2614	Wholesale trade	
0.0302	0.0562	Basic non-ferrous metal and products	Basic chemicals
0.0268	0.0677	Structural metal products	Basic non-ferrous metal and products
0.0256	0.0645	Glass and glass products	
0.0246	0.0621	Other electrical equipment	Other electrical equipment
0.0226	1.7862	Other electrical equipment	
0.0226	0.0442	Sheet metal products	Iron and steel
0.0220	0.0844	Non-ferrous metal ores	
0.0189	0.0273	Wholesale trade	Road transport
0.0174	0.0276	Other electrical equipment	Air and space transport
0.0163	0.0412	Iron and steel	Basic non-ferrous metal and products

(*continued on next page*)

DEI	TEI	Stage 1	Stage 2
0.0160	0.0391	Pulp, paper and paperboard	
0.0157	0.0259	Other electrical equipment	Ceramic products
0.0155	0.0288	Paints	Basic chemicals
0.0152	0.0297	Agricultural, mining and construction machinery	Iron and steel
0.0151	0.0217	Other electrical equipment	Road transport
0.0148	0.0373	Fabricated metal products	Basic non-ferrous metal and products
0.0138	0.0199	Basic non-ferrous metal and products	Road transport
0.0136	0.0196	Road transport	Road transport
0.0135	0.5587	Structural metal products	
0.0128	0.0203	Wholesale trade	Air and space transport
0.0118	0.2663	Fabricated metal products	
0.0113	0.0163	Basic chemicals	Road transport
0.0109	0.0172	Air and space transport	Air and space transport
0.0105	0.0172	Iron and steel	Water transport
0.0101	0.0273	Other mining	
0.0079	0.0168	Other non-metallic mineral products	
0.0055	*0.2733*	*Plastic products*	
6.1782	Sub-total (42.4% of input–output total energy)		
8.4025	Others not listed above (57.6% of total)		

Values in italic: inputs assumed to be covered by the process data.

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